Safety Emergency Science

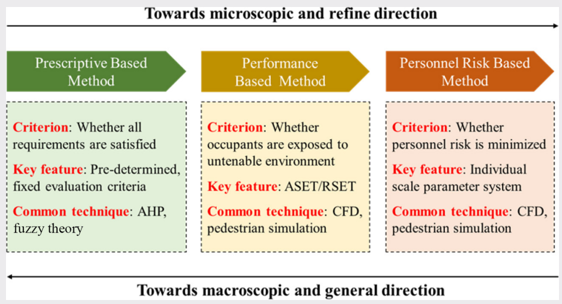
Review Article

Review of fire risk assessment methods at subway stations

Junfeng Chen✉

Cite this article: Chen JF. *Safety Emergency Science*, 2025, **1**(1): 9590001. https://doi.org/10.26599/SES.2025.9590001

ABSTRACT: Fire is a major threat to the safety of subway stations. With various methods and techniques for fire risk assessment at subway stations, this review presents the development process of fire risk assessment research and practice. By summarizing the definitions, regulations, and standards of risk evaluation and assessment in the Chinese subway industry, this work briefly presents the subway risk evaluation/assessment framework in China. Research on the fire risk assessment of subway stations can be divided into three categories according to the starting point and assessment criteria. The key feature, common technique, and typical examples of each category are illustrated. Finally, the potential development of fire risk assessment research for subway stations is discussed. Investigating the characteristics of fire risk, modeling uncertainty in fire risk assessment, and applying new concepts and methods in fire risk assessment practices are key directions for the future.



KEYWORDS: subway station; fire; risk assessment; risk evaluation

1 Introduction

Subways have become a critical component of public transportation systems in metropolises because of their high service capacity and reliable operation schedule (Mao et al., 2021). As the hub facility, subway stations provide services for all passengers entering, transferring, and leaving the subway system, which turns subway stations into busy public places with heavy passenger flow pressures (Zhou et al., 2023). In addition, most subway stations are underground facilities with limited space and narrow access to the outside, which significantly increases the risk of casualties in emergencies (Roh et al., 2009).

Owing to their special structure, subway stations are vulnerable to fire threats. First, the closed environment suggests incomplete combustion with mass production of toxic gases but limited smoke exhaust channels, which leads to fast smoke accumulation and settlement (Hu et al., 2014). Second, underground locations indicate that hot smoke spreads in the same direction as during evacuation, reducing the evacuation efficiency and leading to the occurrence of extreme behavior (Tsukahara et al., 2011). Therefore, improvements in the fire protection design of subway stations have been regarded as a major topic in relevant studies (Long et al., 2023; Wang et al., 2021; Xu et al., 2020).

As various optimization studies have been conducted for fire risk control in subway stations, the objective function or evaluation criterion presents a strong diversification tendency according to the research field (Vermuyten et al., 2016). In ventilation and smoke control research, common evaluation parameters include temperature increase (Long et al., 2020), toxic gas concentration (Liu et al., 2020), and visibility (Meng et al., 2014). In occupant evacuation research, common evaluation parameters include the evacuation time (Chen et al., 2020), distance (Hu et al., 2009), and congestion level (Yang et al., 2013). The definition of fire risk at subway stations is quite flexible depending on the scenario and problem being studied, which illustrates the difficulty in comprehensive fire risk evaluation at subway stations.

As the premise of fire risk control, accurate evaluation of fire risk is a challenging question that has indeed received extensive attention. This work aims to present existing methods for estimating the fire risk of subway stations, which could support precise and effective fire risk control and provide guidance for fire safety design and fire emergency response. The rest of this work is organized as follows: In Section 2, the current risk evaluation requirements in the Chinese subway industry are introduced. In Section 3, the relevant research on subway station fire risk evaluation is summarized. In Section 4, potential directions for future fire risk evaluation methods are discussed. In Section 5, the conclusions are presented.

2 Risk assessment/evaluation requirements for the Chinese subway industry

2.1 Definition of risk assessment and risk evaluation

According to the Risk Management - Risk Assessment

School of Safety Science, Tsinghua University, Beijing 100084, China.

✉ Corresponding author. E-mail: chenjf@cqu.edu.cn

Received: July 7, 2024; Revised: August 29, 2024; Accepted: September 4, 2024

Techniques (IEC 31010:2019) (International Electrotechnical Commission, 2019), risk assessment is the overall process of risk identification, risk analysis, and risk evaluation, which could provide a better understanding of risks for decision-making improvement.

However, different definitions of risk evaluation and risk assessment exist in the Chinese subway system. In fact, both "safety evaluation" and "safety assessment" are used to refer to the risk assessment process in the Chinese subway industry. Risk assessment has been regarded as a method of assessing and promoting safety levels in Chinese subway safety management. Therefore, the word safety evaluation/assessment is adopted in the following part of this section.

The safety evaluation task for the subway industry is in charge of the Ministry of Emergency Management (MEM, 2011). Organizations and individuals are required to be certified by the provincial emergency management department before conducting any safety evaluation project. It focuses on compliance with safety features, which includes multiple rounds of examinations from the planning stage to the operation stage. The safety assessment task for the subway industry is in charge of the Ministry of Transport (MT, 2018). No qualification is required for a safety assessment. It concentrates on the promotion of hierarchical risk control and hidden danger management in the operation stage. The current safety assessment and evaluation process in the Chinese subway industry is summarized in Fig. 1.

Safety evaluation is a mandatory task for all domestic subway lines at present. As a basic requirement, the target of safety evaluation is to judge whether the current situation of the project has fulfilled all safety requirements for facilities, equipment, and management. Therefore, its contents tend to be macroscopic and relatively fixed. However, safety assessment is an extensive requirement that has been implemented in recent years. As an additional step, the target of safety assessment is to identify key risks and hidden dangers during operation and provide feasible control suggestions. Therefore, its contents are mostly from the micro perspective and are highly related to the specific condition of the subway line.

Compared with safety evaluation, safety assessment is more flexible with detailed content. A safety assessment for the subway industry was not officially proposed in the government document until 2018 (MT, 2018), which still requires the support of new theories and methods. Moreover, safety assessments pay more attention to specific stations and tunnels, which are also the most common objects in subway fire studies. Therefore, this work adopts "fire risk assessment" as the title.

2.2 Safety evaluation/assessment of legal and normative system development

The concept of safety preevaluation was first proposed in 1998 by the Ministry of Labor (ML, 1998). In 2002, the work safety law of the People's Republic of China (National People's Congress of China, 2002) was released, which stipulates that the design, construction, and usage of safety facilities must be fully synchronized with the main project. The "triple synchronization" requirement means that safety facilities need to be evaluated at every key stage from design and construction to operation, which is clarified in a notice (NDRC, 2003) issued by the National Development and Reform Commission in 2003. In 2015, the National Development and Reform Commission (NDRC, 2015) and the State Administration of Work Safety (SAWS, 2015) issued another document to emphasize the entity responsibility of enterprises in conducting safety evaluations for all stages and systems of urban rail transit projects.

As a mandatory requirement that has been met for more than 20 years, a standard system has already been constructed for urban rail transit safety evaluation. The Safety Preevaluation Standard of Urban Rail Transit (AQ8004-2007) (SAWS, 2007b) presents the requirements for safety evaluation in the feasibility analysis stage. The Safety Evaluation Standard Before Trial Operation of Urban Rail Transit (AQ8007-2013) (SAWS, 2013) illustrates the requirements for safety evaluation before trial operation. In particular, the standard specifies the requirement of a hot smoke test for performance verification of a fire protection system. The Safety Evaluation Standard on Project Completion of Urban Rail Transit (AQ8005-2007) (SAWS, 2007a) clarifies the safety evaluation requirements for project acceptance before official operation.

The concept of safety assessment was put forward much later. A regulation (MT, 2011) issued by the Ministry of Transport in 2011 proposed for the first time that third-party safety assessment should be organized regularly in the operation stage of urban rail

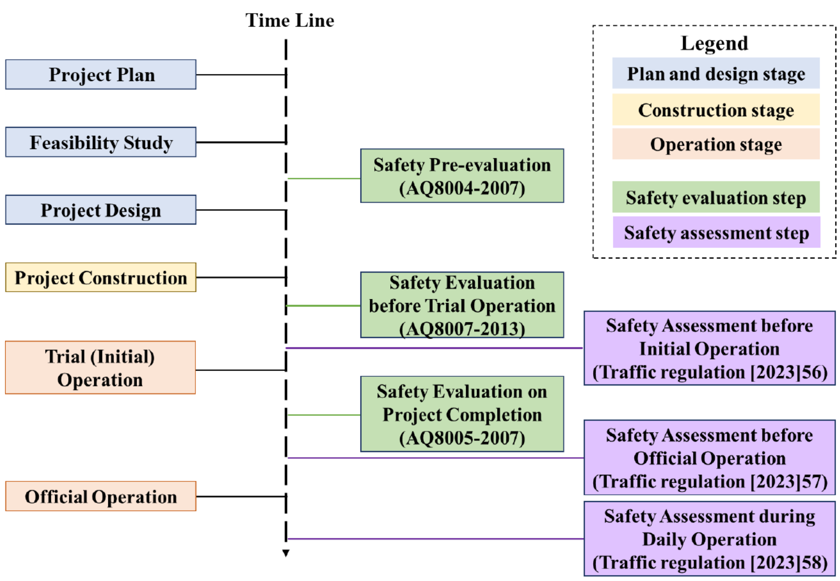


Fig. 1 Current safety assessment and evaluation process of the subway industry in China.

transit. In 2014, the Ministry of Transport (MT, 2014) emphasized the operational safety management of urban rail transit systems and required regular safety assessments during the operation stage.

When the Interim Measures for the Management of Safety Assessment Before and During the Official Operation of Urban Rail Transit (MT, 2019a) was issued in 2019, the implementation guidance was published in the form of two standards. The Regulations for Safety Assessment Before the Official Operation of Urban Rail Transit Part 1: Subway and Light Rail (MT, 2019b) specifies the contents of safety assessment before official operation. Safety assessment has become a precondition for the official operation of all urban rail transit lines. The Regulations for Safety Assessment during the Operation of Urban Rail Transit (MT, 2019c) specify the contents of safety assessment during operation, which clarifies the requirements of hierarchical risk control and hidden danger management in the operation stage.

In 2023, the Ministry of Transport revised the urban rail transit safety assessment regulations (MT, 2023a). The safety assessment task is now divided into three types: safety assessment before initial operation (MT, 2023b), safety assessment before official operation (MT, 2023c), and safety assessment during daily operation (MT, 2023d). In accordance with the new regulations, safety assessment now plays a prominent and leading role in the operational safety of subway systems. The regulation clarifies that safety assessment is a precondition for the initial operation and official operation of any urban rail transit line.

2.3 Fire risk evaluation procedure and content requirements

As shown in Fig. 2, the safety assessment standard system in China has effectively controlled fire risk in the subway industry. Although the operation line length has increased by more than 26 times during the past 25 years, the number of fire accidents in subway systems has remained similar. With the implementation of new regulations after the 2010s, a standardized safety evaluation process has become mandatory for all subway lines, which has led to a downward trend in the number of subway fire accidents. In this section, the requirements of fire risk evaluation in the current standard system are introduced in detail.

The Safety Evaluation Standard Before Trial Operation of Urban Rail Transit (AQ8007-2013) (SAWS, 2013) adopts an independent chapter to illustrate the requirements of hot smoke tests. The hot smoke test aims to verify the reliability and effectiveness of the fire alarm system, smoke exhaust system, accident lighting system, and evacuation facilities in fire scenarios.

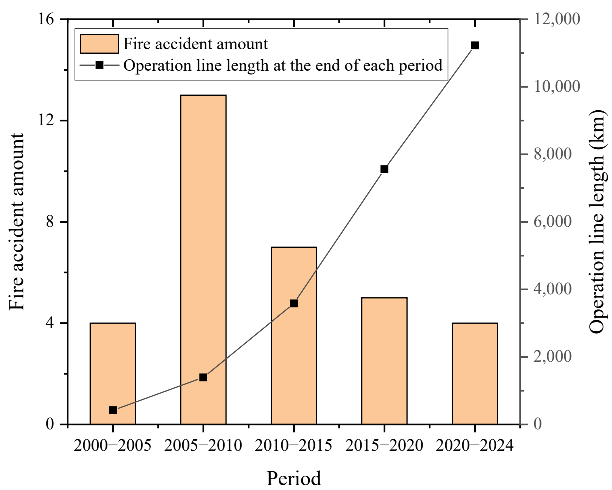


Fig. 2 Development of subway systems and fire accident history in China (Zhu, 2018).

The standard requirements of the fire source form, measurement system composition, test process, and evaluation criteria are presented. The use of a methanol oil pool fire with nontoxic smoke-generating materials as the fire source to display the smoke spread characteristics is recommended. The measurement system should include temperature, gas concentration, airflow velocity, thermal imaging, and video equipment. The test process is composed of experiments in a station hall, a station platform, a station tunnel, and an interval tunnel. The evaluation criteria are partly performance-based and include a temperature limitation of 180 °C above 1.5 m, a temperature limitation of 60 °C below 1.5 m, and an available evacuation time of more than 6 min. While prescriptive-based criteria such as a 1.5 m/s airflow velocity at the opening of stairs, a detection and alarm time of less than 1 min, and an evacuation facility mode switchover time of less than 1 min are also included.

Guidance for fire risk assessment of assembly occupancy (MEM, 2016) is another standard that specifies the content of fire risk assessment for crowded places such as subway stations. As a standard mainly based on prescriptive methods, it lists onsite inspection requirements in aspects such as building fire prevention, evacuation safety, firefighting facilities, and fire safety management. However, quantitative methods such as fire dynamics simulation and evacuation simulation are also suggested for necessary conditions.

Considering the special structure and fire risk characteristics of subway interval tunnels, a standard entitled Field Test Technology and Method for Fire in Metro Interval Tunnel (T/COSHA 019-2023) (China Occupational Safety and Health Association, 2023) was published recently. This standard specifies the methods, contents, and requirements of onsite fire tests in subway tunnels in the initial and official operation stages.

3 Fire risk assessment methods for subway stations

Although only a few studies have focused on fire risk assessment methods for subway stations, most studies related to subway fires have had to define a standard to clarify the advantages of the research results, which usually involves a fire risk assessment strategy. According to the differences in the starting points and assessment criteria, the fire risk assessment methods for subway stations can be divided into three categories, which are summarized in Fig. 3 and discussed separately below.

3.1 Prescriptive-based methods

As the traditional method in building fire risk assessment, the prescriptive-based method plays an important role in subway fire protection regulation in various countries (MHURD, 2013; NFPA, 2023). The basic concept is to test whether a building has an acceptable level of fire risk according to uniform qualitative (such as the installation of fire doors or water spray systems) and quantitative (such as the ventilation volume and number of stairs) criteria. Although many studies (Lo et al., 2004; Wolski et al., 2000) have highlighted the disadvantage of prescriptive-based methods in terms of flexibility, diversity, and cost effectiveness, fixed index requirements are still widely adopted because of the advantages of being easy to check and having low requirements for designers (Liu et al., 2006).

In recent years, fire risk assessment research and practice

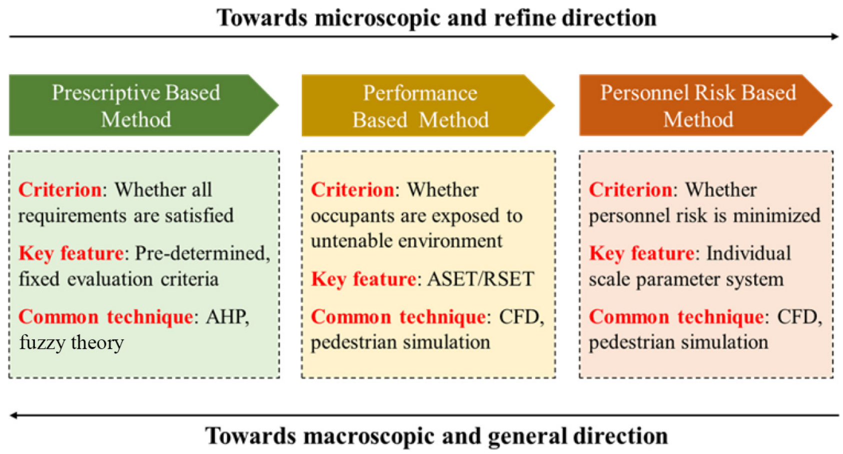


Fig. 3 Overview of the fire risk evaluation methods for subway stations.

related to subway stations have further extended the prescriptive concept. With the idea of a predetermined index system unchanged, related research explores more comprehensive fire risk assessment methods by refining parameter systems or risk calculation techniques.

The analytic hierarchy process (AHP) is a common method used in relevant studies (Hou et al., 2014; Li et al., 2010; Song et al., 2018; Yan and Wang, 2021) to determine index weights and calculate overall risk levels. Various index systems have been constructed in these studies from various dimensions, such as fire protection design, daily management, emergency response, equipment status, and personnel ability. Fuzzy theory is another frequently used method for index weight estimation. Owing to its good adaptability, this theory is integrated with probability theory (Mi et al., 2015), the fault tree method (Chen, 2013; Zhu, 2018), or the Petri net method (Chu et al., 2016; Zhao, 2018) to characterize the overall fire risk level at subway stations. Some scholars have also adopted the neural network method (Wang et al., 2017), Bayesian network (Wang, 2022), or TOPSIS method (Ju et al., 2022) to integrate the index system for overall risk level calculation.

Diverse fire risk assessment methods and index systems have been constructed in prescriptive-based studies. However, the expert evaluation method is commonly used to provide additional data support in steps such as parameter selection, weight calculation, and fire probability/consequence estimation. Thus, the accuracy of fire risk assessment results is inevitably influenced by subjective impacts (Mi et al., 2015), which constrains the reliability of the method.

Therefore, as early as the 1980s, scholars from the USA, UK, Australia, Japan, China, and other countries began to establish performance-based designs to replace prescriptive-based designs (Ni, 2001). The change in fire design has created a new branch of the fire risk assessment method, which is discussed in Section 3.2.

3.2 Performance-based methods

The performance-based method focuses on ensuring the safety of all occupants rather than satisfying all parameter requirements (Liu et al., 2006). Considering that the structure, use, fire type, and occupant distribution in different buildings might vary greatly, adopting uniform parameter requirements does not represent the same acceptable safety level for all buildings (Xiao, 2002). Instead, if the overall performance is taken as the design target, a more flexible and effective fire protection design could be achieved with a focus on occupant safety (Huo and Yuan, 2003).

The definition and assessment of "performance" is the core step of performance-based design (Mei et al., 2005). After long-term practice, most scholars accepted the ASET/RSET concept for fire protection performance assessment (Babrauskas et al., 2010). The available safe energy time (ASET) represents the time interval between the moment of ignition and the moment when the indoor environment reaches the human tolerance limit. The required safe energy time (RSET) represents the time interval between the moment of ignition and the moment when all occupants leave the building. When the ASET is greater than the RSET, all occupants can leave the building before the fire environment becomes intolerable, indicating that the fire protection performance of the building satisfies occupant safety requirements.

With the development of computer technology, numerical simulation (Qu and Chow, 2013; Xie et al., 2021) has become the most common method for estimating ASET and RSET at subway stations. For the prediction of smoke spread and calculation of the ASET, computational fluid dynamics tools such as Fluent and FDS are the primary methods (Wang, 2011). For the prediction of occupant evacuation and calculation of the RSET, micro pedestrian simulation models such as the social force model and cellular automata are the primary methods (Mandal et al., 2023). Several experimental studies have also reported ASET (Luo et al., 2014; Xu et al., 2021) and RSET (Jeon and Hong, 2009; Yoon et al., 2013) data in real fire scenarios.

However, the ASET/RSET concept was first derived from a one-room scenario (Cooper, 1983), which ignores the spatial heterogeneity of fire risk in the studied area (Poon, 2014). In addition, the one-dimensional method equates fire risk with evacuation time (Khorasani-Zavareh et al., 2019), which simplifies the randomness of smoke spread and occupant behavior (Sime, 1986). The ASET/RSET concept simplifies the evacuation performance of all occupants into the evacuation performance of the last occupant left, which fails to provide a comprehensive evaluation of the fire risk of all occupants. The applicability of the ASET/RSET method for fire risk evaluation at subway stations deserves further discussion (Zhang et al. 2019).

After recognizing the shortcomings of the ASET/RSET concepts, several scholars modified the assessment technique to achieve a more comprehensive risk evaluation. Poon (2014) introduced a dynamic perspective to analyze the spatial-temporal evolution of ASET/RSET during fire development. Schröder et al. (2020) proposed a map-based method to model the distribution of ASET/RSET in a fire scenario. The fire risk around the entire building can be intuitively presented with a difference map of ASET minus RSET. Zhang et al. (2019) evaluated the overall fire risk level around a station according to the ratio of RSET and ASET in critical locations and identified the most dangerous scenario.

Constrained by the ASET/RSET concept, it is easy for the performance-based method to evaluate whether a building is safe but difficult to analyze how safe it is. In other words, the characterization of the "performance" of a large building such as a subway station in a fire scenario with one global parameter seems unrealizable. To model the risk of occupants being exposed to a fire environment, scholars have begun to explore individual-based risk assessment methods, which are discussed in Section 3.3.

3.3 Personnel risk-based method

As the most vulnerable subject in fire scenarios, the safety of occupants is the crucial requirement in most fire protection standards (ISO, 2012; MHURD, 2022; NFPA, 2024). Therefore, subway station fire risk can be estimated in terms of overall personnel risk during the evacuation process under fire conditions. To evaluate the risk level of the coupling process between fire development and personnel evacuation, two comprehensive methods, multidimensional evaluation and effective dose evaluation, are proposed.

The first strategy is to increase the dimensions of risk characterization. Since the fire risk in complex buildings cannot be fully described with one parameter, more evaluation dimensions are introduced to expand the comprehensiveness of the method. Chen et al. (2015) established a personnel risk assessment index system from four dimensions: survival rate, congestion risk, evacuation efficiency, and evacuation orderliness. The evacuation risk in typical subway station fire scenarios is evaluated via integrated fire and evacuation simulations. Marzouk and Mohamed (2019) adopted the BIM method and a multiagent simulation model to calculate building evacuation performance. The personal fire risk is evaluated with eight parameters, including the safety margin, successful evacuation ratio, congestion factor, conflict effect, and high-density effect. Chen et al. (2021) proposed an evacuation risk parameter system from both maximum risk and average risk perspectives. The overall risk level of typical scenarios at a subway station is evaluated with a dimensionless evacuation risk index.

The second strategy is to use the effective dose concept to estimate individual risk. With the fractional effective dose concept proposed by Purser and McAllister (2016), the cumulative effect of multiple fire smoke components can be evaluated. As a dimensionless variable between 0 and 1, FED represents the ratio of the cumulative dose personnel receive to the incapacitated dose, which could characterize the risk of personnel being exposed to a fire environment. Qu et al. (2013) adopted the FED concept to establish a quantitative risk assessment method for casualty probability and location estimation in road tunnel fire scenarios. Krasuski and Krenski (2019) constructed an integrated fire-evacuation simulator with FED as the fire risk assessment parameter. The spatial distribution of the fire risk level is given with a probability description. Yao et al. (2013) proposed a fire hazard map based on the FED concept. The fire risk ranking parameter is defined to combine the effects of temperature, toxicity, and hypoxia for life safety evaluation in fire environments. Chen et al. (2023) defined a fire risk index that integrates the ASET/RSET concept and FED concept for fire risk assessment at subway stations. The maximum potential effective dose is regarded as an indicator of the fire risk level of an area. Then, a grid-based fire risk map can be acquired to visually display the fire risk distribution.

A common logic of the above studies is to characterize the individual risk in a fire environment by modeling the fire smoke spread process and personnel evacuation process at the same time. The multidimensional method pays more attention to congestion and stamped risk during the evacuation process, which is more applicable for evacuation facilities and strategy design optimization. The effective dose method focuses on the fire/smoke exposure risk during the evacuation process, which is more applicable for ventilation and smoke prevention facilities and strategy design optimization.

After the risk level of all personnel in a fire scenario is acquired, the global fire risk level can be revealed via the personnel risk-based method. By changing the fire risk evaluation target from the evacuation time to the occupant risk, the personnel risk-based method is more consistent with the life safety protection idea in fire safety design.

4 Discussions

The modeling of subway station fire risk is still in the exploratory stage. Although various studies have been conducted in fields such as fire dynamics, evacuation dynamics, and emergency response strategies, quantitative investigations of fire risk characteristics at subway stations have always been ignored. A potential reason is that fire risk assessment is usually an intermediate step and a tool to support subsequent optimization. Evaluating the fire risk distribution itself is of little significance to the operation of subway stations. However, improvements in fire protection design, smoke control strategies, and emergency evacuation schemes with the assistance of fire risk evaluation could provide effective guidance for policy makers. As the evaluation criterion, or rather the objective function, the definition of the fire risk level has not attracted sufficient attention or reached a consensus, which would reduce the optimization effectiveness for occupant safety protection. In the following paragraphs, several challenges currently faced in the field of subway station fire risk assessment are summarized.

The first challenge is the definition of fire risk at subway stations. Risk is often regarded as a combination of probability and consequence. With respect to occurrence probability analysis, a common strategy in practice is to make qualitative judgments on the basis of a fire hazard checklist or score table. Subjectively selected scenarios according to the expected probability are usually adopted in related research. With respect to consequence severity analysis, indirect estimation methods such as checklists and field fire tests are commonly used in practice. Direct estimates of human and economic losses are also rare in related research. Modeling the spatial distribution and temporal evolution of fire risk at subway stations remains a challenge.

The second challenge in the assessment of fire risk at subway stations is uncertainty throughout the evaluation procedure. For the prescriptive-based method, the key source of uncertainty is the subjective influence of outside experts and the researcher himself. This kind of uncertainty can be reduced by technical methods, but it cannot be eliminated due to data insufficiency. For performance-based methods, the key source of uncertainty is the deviations between experimental/numerical results and real conditions. The uncertainties in steps such as data input, scenario design, and model construction are usually ignored. The repeatability and reproducibility of the output results are rarely tested. For the personnel risk-based method, the people themselves are the key source of uncertainty. The randomness and complexity of human psychology and behavior make accurate prediction of the evacuation process difficult. The heterogeneity of human physiology increases the difficulty in evaluating individual risk in a fire environment. Considering the superposition of multiple sources of uncertainty, more experimental data, reliable simulation tools, and uncertainty analysis methods are needed to support the fire risk assessment of subway stations.

The third challenge is the extension of fire risk assessment methods throughout the life cycle of subway stations. The existing risk assessment research often concentrates on improving ventilation and evacuation strategies for subway stations in operation. Although fire risk assessment is required for every subway station in the design stage, evaluation results aimed at satisfying specific criteria cannot effectively guide the optimization of fire protection design. In addition, occupant safety-oriented fire risk evaluations are rarely carried out in the renovations of existing stations, which makes renovation possible to increase the fire risk at the station. Given the large number of subway stations that have been built, this blind spot needs to be fully filled with new fire risk assessment methods.

The practice of subway fire risk assessment has relatively lagged behind the research progress. The evaluation methods in current standards are mostly prescriptive-based and partly performance-based. However, with the expansion of subway networks, the vehicle type, fire protection system composition, and geometric structure of subway stations have shown diverse trends. The relatively fixed and conservative prescriptive-based methods are becoming increasingly less suitable for newly built stations. The integration of performance-based and personnel risk-based concepts into the existing risk assessment standard system should receive increased attention. The adoption of individual risk levels instead of predetermined criteria as guides for station fire protection design is a direction worthy of further discussion.

5 Conclusions

Fire is an important risk to subway stations. This work first reviews the current subway risk evaluation/assessment regulations and standards system in China, with a special introduction to fire risk assessment requirements. The research on fire risk assessment at subway stations can be summarized into three categories: prescriptive-based methods, performance-based methods, and personnel risk-based methods. Finally, the problems that deserve further exploration in the field of subway station fire risk assessment are discussed.

This work aims to present the development process of subway station fire risk assessment research and Chinese subway station risk evaluation/assessment practices. The review suggests a trend of evaluation criterion refinement from a predetermined index to an individual risk level. The evaluation object gradually changed from the subway station itself to the performance of the subway station under fire conditions. The current standard and regulation system lags relatively behind research progress. However, relevant studies have focused mostly on specific station cases, which is insufficient for updating the standard system. Systematic research is urged to change the fire risk evaluation orientation from the prescriptive mode toward the performance mode or even the individual risk mode.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (52374210, 52104198, and 72091512).

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

References

Babrauskas, V., Fleming, J. M., Russell, B. D. 2010. RSET/ASET, a flawed concept for fire safety assessment. *Fire and Materials*, **34**: 341–355.

Chen, J., Liu, C., Meng, Y., Zhong, M. 2021. Multi-Dimensional evacuation risk evaluation in standard subway station. *Safety Science*, **142**: 105392.

Chen, J., Zhong, M., Qiu, P., Long, Z., Chen, J. 2023. Mapping the fire risk in buildings: A hybrid method of ASET-RSET concept and FED concept. *Reliability Engineering & System Safety*, **240**: 109571.

Chen, M. 2013. Study on fire risk assessment and control of subway based on the fuzzy theory. Xiamen: Huaqiao University.

Chen, Y., Cai, Y., Li, P., Zhang, G. 2015. Study on evacuation evaluation in subway fire based on pedestrian simulation technology. *Mathematical Problems in Engineering*, **2015**: 357945.

Chen, Y., Wang, C., Hui Yap, J. B., Li, H., Zhang, S. 2020. Emergency evacuation simulation at starting connection of cross-sea bridge: Case study on Haicang Avenue Subway Station in Xiamen Rail Transit Line. *Journal of Building Engineering*, **29**: 101163.

China Occupational Safety and Health Association. 2023. Field test technology and method for fire in metro interval tunnel. Beijing: China Occupational Safety and Health Association.

Chu, P. Y., Liu, L., Yin, J. S. 2016. On the subway fire risk assessment based on the dynamically variable weight Petri net. *Journal of Safety and Environment*, **16**(6): 39–44. (in Chinese)

Cooper, L. Y. 1983. A concept for estimating available safe egress time in fires. *Fire Safety Journal*, **5**: 135–144.

Hou, Y. S., Li, Y. F., Shi, B. W., Zhao, M. 2014. Fire risk assessment of a subway transfer station. *Fire Science and Technology*, **33**(11): 1326–1329. (in Chinese)

Hu, L., Wu, L., Lu, K., Zhang, X., Liu, S., Qiu, Z. 2014. Optimization of emergency ventilation mode for a train on fire stopping beside platform of a metro station. *Building Simulation*, **7**: 137–146.

Hu, Q. M., Fang, W. N., Li, G. Y., Ding, L. 2009. Influence of exit layout of a metro station on pedestrian evacuation. *Journal of the China Railway Society*, **31**(3): 111–115. (in Chinese)

Huo, R., Yuan, H. 2003. *Analysis and Design of Performance-based Building Fire Protection*. Hefei: Anhui Science and Technology Press.

International Electrotechnical Commission. 2019. Risk management-risk assessment techniques. Geneva: IEC.

International Organization for Standardization (ISO). 2012. Life-threatening components of fire-guidelines for the estimation of time to compromised tenability in fires. Geneva: ISO.

Jeon, G. Y., Hong, W. H. 2009. An experimental study on how phosphorescent guidance equipment influences on evacuation in impaired visibility. *Journal of Loss Prevention in the Process Industries*, **22**: 934–942.

Ju, W., Wu, J., Kang, Q., Jiang, J., Xing, Z. 2022. Fire risk assessment of subway stations based on combination weighting of game theory and TOPSIS method. *Sustainability*, **14**: 7275.

Khorasani-Zavareh, D., Nouri, F., Kavousi, A., Mohammadi, R. 2019. A system approach on safe emergency evacuation in Subways: A systematic literature review. *Archives of Trauma Research*, **8**: 119.

Krasuski, A., Krenski, K. 2019. A-evac: The evacuation simulator for stochastic environment. *Fire Technology*, **55**: 1707–1732.

Li, Y. F., Shi, B. W., Wang, C., Li, J. M., Fan, H. M. 2010. Study on fire risk assessment system for urban underground rail traffic: A subway station is selected as example. *Journal of Disaster Prevention and Mitigation Engineering*, **30**(6): 680–684. (in Chinese)

Liu, F., Liu, Y., Xiong, K., Weng, M., Wang, J. 2020. Experimental and numerical study on the smoke movement and smoke control strategy in a hub station fire. *Tunnelling and Underground Space Technology*, **96**: 103177.

Liu, J., Cheng, Y. P., Gao, Y. F. 2006. Several problems to be considered in moving toward performance-based fire safety codes. *Journal of Disaster Prevention and Mitigation Engineering*, **26**(2): 235–240. (in Chinese)

Lo, S. M., Fang, Z., Lin, P., Zhi, G. S. 2004. An evacuation model: The SGEM package. *Fire Safety Journal*, **39**: 169–190.

Long, Z., Liu, C., Yang, Y., Qiu, P., Tian, X., Zhong, M. 2020. Full-scale experimental study on fire-induced smoke movement and control in an underground double-island subway station. *Tunnelling and Underground Space Technology*, **103**: 103508.

Long, Z., Zhong, M., Chen, J., Cheng, H. 2023. Study on emergency ventilation strategies for various fire scenarios in a double-island subway station. *Journal of Wind Engineering and Industrial Aerodynamics*, **235**: 105364.

Luo, N., Li, A., Gao, R., Tian, Z., Hu, Z. 2014. Smoke confinement utilizing the USME ventilation mode for subway station fire. *Safety Science*, **70**: 202–210.

Mandal, T., Ramachandra Rao, K., Tiwari, G. 2023. Evacuation of metro stations: A review. *Tunnelling and Underground Space Technology*, **140**: 105304.

Mao, R., Bao, Y., Duan, H., Liu, G. 2021. Global urban subway development, construction material stocks, and embodied carbon emissions. *Humanities and Social Sciences Communications*, **8**: 83.

Marzouk, M., Mohamed, B. 2019. Integrated agent-based simulation and multi-criteria decision making approach for buildings evacuation evaluation. *Safety Science*, **112**: 57–65.

Mei, X. J., Lan, B., Zhang, Z. J., Zhu, H. W. 2005. Preliminary discussion on performance-based assessment of fire fighting for buildings. *China Safety Science Journal*, **15**(8): 51–56, 115.

Meng, N., Hu, L., Wu, L., Yang, L., Zhu, S., Chen, L., Tang, W. 2014. Numerical study on the optimization of smoke ventilation mode at the conjunction area between tunnel track and platform in emergency of a train fire at subway station. *Tunnelling and Underground Space Technology*, **40**: 151–159.

Mi, H. F., Xiao, G. Q., Wang, L. Y., Xue, S. C., Wang, Q. H. 2015. On the fire risk evaluation for the subway station based on the probability fuzzy theory. *Journal of Safety and Environment*, **15**(5): 16–20. (in Chinese)

Ministry of Emergency Management of the People's Republic of China (MEM). 2011. Construction project safety facilities "three simultaneous" supervision and administration measures. Beijing: Ministry of Emergency Management.

Ministry of Emergency Management of the People's Republic of China (MEM). 2016. Guidance on fire risk assessment of assembly occupancy: X/T 1369-2016. Beijing: State Administration of Work Safety.

Ministry of Housing and Urban-Rural Development of the People's Republic of China (MHURD). 2013. Code for design of metro. Beijing: China Architecture Publishing & Media Coporation.

Ministry of Housing and Urban-Rural Development of the People's Republic of China (MHURD). 2022. General specification for building fire protecion. Beijing: China Planning Press.

Ministry of Labor of the People's Republic of China (ML). 1998. Administrative measures for pre-evaluation of labor safety and health of construction projects. Beijing: Ministry of Labor.

Ministry of Transport of the People's Republic of China (MT). 2011. Notice on strengthening operation management of urban rail transit. Beijing: Ministry of Transport.

Ministry of Transport of the People's Republic of China (MT). 2014. Notice on strengthening operation safety management of urban rail transit. Beijing: Ministry of Transport.

Ministry of Transport of the People's Republic of China (MT). 2018. Urban rail transit operation management provisions. Beijing: Ministry of Transport.

Ministry of Transport of the People's Republic of China (MT). 2019a. Interim measures for the management of safety assessment before and during the official operation of urban rail transit. Beijing: Ministry of Transport.

Ministry of Transport of the People's Republic of China (MT). 2019b. Regulations for safety assessment before the official operation of urban rail transit part 1: Subway and light rail. Beijing: Ministry of Transport.

Ministry of Transport of the People's Republic of China (MT). 2019c. Regulations for safety assessment during the operation of urban rail transit. Beijing: Ministry of Transport.

Ministry of Transport of the People's Republic of China (MT). 2023a. Measures for the management of operational safety assessment of urban rail transit. Beijing: Ministry of Transport.

Ministry of Transport of the People's Republic of China (MT). 2023b. Regulations for safety assessment before the initial operation of urban rail transit. Beijing: Ministry of Transport.

Ministry of Transport of the People's Republic of China (MT). 2023c. Regulations for safety assessment before the official operation of urban rail transit. Beijing: Ministry of Transport.

Ministry of Transport of the People's Republic of China (MT). 2023d. Regulations for safety assessment during operation of urban rail transit. Beijing: Ministry of Transport.

National Development and Reform Commission (NDRC). 2003. Notice on strengthening the "three synchronization" work of safety facilities for construction projects. Beijing: National Development and Reform Commission.

National Development and Reform Commission (NDRC). 2015. Notice of national development and reform commission on strengthening the management of urban rail transit planning and construction. Beijing: National Development and Reform Commission.

National Fire Protection Asosiation (NFPA). 2023. Standard for fixed guide way transit and passenger rail systems. Quincy: NFPA.

National Fire Protection Asosiation (NFPA). 2024. Life safety code. Quincy: NFPA.

National People's Congress of China. 2002. Work safety law of the People's Republic of China. Beijing: National People's Congress of China.

Ni, Z. P. 2001. Summary of foreign research on performance-based building fire protection code. *Fire Technique and Products Information*, **14**(10): 3–6. (in Chinese)

Poon S. 2014. A dynamic approach to ASET/RSET assessment in performance based design. In: Proceedings of the International Conference on Performance-based Fire and Fire Protection Engineering.

Purser, D. A., Mcallister, J. L. 2016. Assessment of hazards to occupants from smoke, toxic gases, and heat. In: *SFPE Handbook of Fire Protection Engineering*. Hurley, M. J., Gottuk, D., Hall, J. R., Eds. Springer New York, 2308–2428.

Qu, L., Chow, W. K. 2013. Common practices in fire hazard assessment for underground transport stations. *Tunnelling and Underground Space Technology*, **38**: 377–384.

Qu, X., Meng, Q., Liu, Z. 2013. Estimation of number of fatalities caused by toxic gases due to fire in road tunnels. *Accident Analysis & Prevention*, **50**: 616–621.

Roh, J. S., Ryou, H. S., Park, W. H., Jang, Y. J. 2009. CFD simulation and assessment of life safety in a subway train fire. *Tunnelling and Underground Space Technology*, **24**: 447–453.

Schröder, B., Arnold, L., Seyfried, A. 2020. A map representation of the ASET-RSET concept. *Fire Safety Journal*, **115**: 103154.

Sime, J. 1986. Perceived time available: The margin of safety in fires. *Fire Safety Science*, **1**: 561–570.

Song, Z. Z., Song, W. B., Lin, L. 2018. Fire risk assessment of subway station based on multi-level extension evaluation method. *Manufacturing Automation*, **40**(12): 26–30, 41. (in Chinese)

State Administration of Work Safety (SAWS). 2007a. Safety evaluation standard on project completion of urban rail transit. Beijing: State Administration of Work Safety.

State Administration of Work Safety (SAWS). 2007b. Safety pre-evaluation standard of urban rail transit. Beijing: State Administration of Work Safety.

State Administration of Work Safety (SAWS). 2013. Safety evaluation standard beforee trial operation of urban rail transit. Beijing: State Administration of Work Safety.

State Administration of Work Safety (SAWS). 2015. Construction project safety facilities "three simultaneous" supervision and administration measures. Beijing: State Administration of Work Safety.

Tsukahara, M., Koshiba, Y., Ohtani, H. 2011. Effectiveness of downward evacuation in a large-scale subway fire using Fire Dynamics Simulator. *Tunnelling and Underground Space Technology*, **26**: 573–581.

Vermuyten, H., Beliën, J., De Boeck, L., Reniers, G., Wauters, T. 2016. A review of optimisation models for pedestrian evacuation and design problems. *Safety Science*, **87**: 167–178.

Wang, B. 2011. Comparative research on FLUENT and FDS's numerical simulation of smoke spread in subway platform fire. *Procedia Engineering*, **26**: 1065–1075.

Wang, J. B., Peng, L. B., Li, N., Zhang, S. 2017. Fire risk evaluation of subway station based on PCA-RBF neural network. *Industrial Safety and Environmental Protection*, **43**(9): 67–70. (in Chinese)

Wang, K., Cai, W., Zhang, Y., Hao, H., Wang, Z. 2021. Numerical simulation of fire smoke control methods in subway stations and collaborative control system for emergency rescue. *Process Safety and Environmental Protection*, **147**: 146–161.[

Wang, T. 2022. Research on risk assessment of rail transit underground stations to fire disasters using bayesian network. Master Thesis. Chongqin: Chongqin University.

Wolski, A., Dembsey, N. A., Meacham, B. J. 2000. Accommodating perceptions of risk in performance-based building fire safety code development. *Fire Safety Journal*, **34**: 297–309.

Xiao, X. F. 2002. Develop performance-based fire protection design to meet the challenge of joining WTO. *Fire Science and Technology*, **21**(5): 14–16. (in Chinese)

Xie J., Chen K., Kwan, T. H., Yao Q. 2021. Numerical simulation of the fire emergency evacuation for a metro platform accident. *Simulation*, **97**: 19–32.

Xu, D., Li, Y., Li, J., Zhang, J., Li, J. 2021. Investigation on the effect of platform height on smoke characteristics of fire scenarios for subway stations. *Sustainability*, **13**: 10584.

Xu, H., Tian, C., Li, Y. 2020. Emergency evacuation simulation and optimization for a complex rail transit station: A perspective of promoting transportation safety. *Journal of Advanced Transportation*, **2020**: 8791503.

Yan, Z., Wang, Y. 2021. Developing a subway fire risk assessment model based on analysis theory. *Mathematical Problems in Engineering*, **2021**: 5549952.

Yang, P., Li, C., Chen, D. 2013. Fire emergency evacuation simulation based on integrated fire–evacuation model with discrete design method. *Advances in Engineering Software*, **65**: 101–111.

Yao, W., Huang, H., Shen, S., Qiao, L., Wang, W., Zhang, H. 2013. Fire risk mapping based assessment method applied in performance based design. *Fire Safety Journal*, **56**: 81–89.

Yoon, S. H., Lee, M. J., Yee, J. J. 2013. An experimental study on evacuation times in a subway station using evacuation parameters. *Journal of Asian Architecture and Building Engineering*, **12**: 93–100.

Zhang, L., Wu, X., Liu, M., Liu, W., Ashuri, B. 2019. Discovering worst fire scenarios in subway stations: A simulation approach. *Automation in Construction*, **99**: 183–196.

Zhao, J. 2018. Subway fire risk assessment based on FPN model and FAHP. Master Thesis. Qingdao: Qingdao University of Technology.

Zhou, Y., Chen, J., Zhong, M., Li, Z., Zhou, W., Zhou, Z. 2023. Risk analysis of crowd gathering on metro platforms during large passenger flow. *Tunnelling and Underground Space Technology*, **142**: 105421.

Zhu, W. 2018. Fire risk assessment of subway operation based on fuzzy fault. Master Thesis. Beijing: Beijing Jiaotong University.

Junfeng Chen is a Ph.D. candidate in School of Safety Science, Tsinghua University. His primary research interests are the fire protection and smoke exhaust in subway stations.